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Trains of Taylor bubbles over hot nano-textured mini-channel surface

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ABSTRACT

To enhance heat transfer in forced convective boiling the mini-channel bottom was amended by nano-textured structures – periodic rectangular mats of electrospun polymer nanofibers. The fibers were about several hundreds of nanometer in diameter. The test fluid was FC-72. The flow in mini-channels contained trains of the Taylor bubbles. The role of the nanofibers was to retain the warm mini-channel bottom wetted, to prevent dry-out and thus to enhance the heat removal rate. In the present experiments the time-average heat flux at the nanofiber-coated domains was found to be 1.6 times higher than that at the uncoated ones. Accordingly, a significant decrease (by 5–8 K) in the superheat was observed. The heat transfer coefficient at the nanofiber mat-coated domains was found to be an order of magnitude higher than that at the uncoated domains. Such significant enhancement of heat transfer results from the fact that nanofiber mats facilitate wetting of the surface under the passing Taylor bubbles, thus delaying formation of vapor layer at the channel bottom.

1. Introduction

The need for removal of large amounts of heat from small-scale semiconductor units imposes extremely challenging requirements on cooling systems [1]. Flow boiling in micro- and mini-channels holds great potential for thermal management of high-power density miniature electronic devices. One of the most important flow regimes during flow boiling in micro- and mini-channels is the slug flow regime. In this regime large elongated vapor Taylor bubbles, with the smallest dimension restricted by the channel cross-section, flow in train along the channel. The heat transfer in this regime is determined by evaporation of thin film separating the elongated bubbles from the heated walls [2,3]. However, the liquid film around the elongated bubbles has been shown to dry out partially or completely [3,4], which adversely affects the heat transfer. One of the major problems in the enhancement of heat transfer during flow boiling in micro- and mini-channels is finding the way to keep the heater wall around the flowing elongated bubbles wetted.

Several previous attempts have been made to enhance heat transfer during nucleate boiling and flow boiling by modification of the heater surface [5–7]. In particular, nanowires have been fabricated at the walls of micro-channels using a two-step electroless etching process, which resulted in stabilization of flow and boiling process and increase of removed heat flux in certain cases by about 40% [6]. Nano-texturing has been also rendered by electrospun nanofibers to enhance heat removal rate from high-power micro-electronics by drop/spray cooling and in pool boiling and to prevent Leidenfrost effect when coolant droplets impact onto high-temperature surfaces [8–16]. These results show that heat removal at such nano-textured surfaces can be as high as 1 kW/cm^2.

In the present work we demonstrate that using nano-textured mini-channel surfaces prevents dry-out underneath the passing trains of the Taylor bubbles, which opens an effective way for heat transfer enhancement in forced convective boiling. This is achieved by amending the mini-channel bottom with nano-textured periodic rectangular mats of electrospun polymer nanofibers of the order of several hundred nanometers in diameter. In the present mini-channel experiments the flow of fluorinert fluid FC-72 with trains of the Taylor bubbles over the nanofibers retained the heated channel bottom wetted. As a result, dry-out was prevented leading to an enhancement in heat removal rate. The time-average heat flux at the nanofiber-coated domains was found to be up to 1.6 times

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higher than that at the uncoated ones. Accordingly, a significant decrease (by 5–8 K) in the superheat was observed for the Reynolds numbers in the 313–432 range with the applied heat flux being in the 28–36 kW/m^2 range. An order of magnitude increase in the heat transfer coefficient has been revealed. The significant enhancement of the heat transfer results from the fact that nanofiber mats facilitate wetting of the surface under the passing Taylor bubbles, thus delaying formation of vapor layer at the channel bottom. The interstices of the nanofiber coating act as the nucleation sites facilitating formation of tiny bubbles, which eventually results in a higher heat removal rate from the surface at a reduced superheat.

2. Experimental method

2.1. Preparation of nanofiber mats

Polyacrylonitrile (PAN; M_w = 150 kDa) was obtained from Polysciences Inc., n-dimethyl formamide (DMF) anhydrous-99.8%, was obtained from Sigma–Aldrich. Electrospinning was conducted with the 9 wt% PAN solutions in DMF. A standard electrospinning setup [17–19] was used to prepare PAN nanofiber mats over the stainless steel foils (20-mm foils of X5CrNi18-10 steel). The nanofibers were electrospun on the foil for 45 s. The fiber diameter was in the 100–300 nm range and the mat thickness was in the 6–15 μm range. Various periodic nanofiber patch patterns of different size and pitch were obtained by removing sections of the original continuous nanofiber mats using ethanol-wetted cottons, without disturbing the corresponding nanofiber patch area and avoiding any scratch or serration on the foil and between the patches. The nanofiber mat adhesion to the foil was enhanced by wetting the edges of the patches with ethanol while removing the extra material, which also helped to avoid any additional edge effect during the experiments.

2.2. Experimental setup and method for heat flux measurement

The experimental setup for investigation of flow boiling in a mini-channel, the instrumentation used, the experimental procedure and the data processing have been described in [4,20]. The

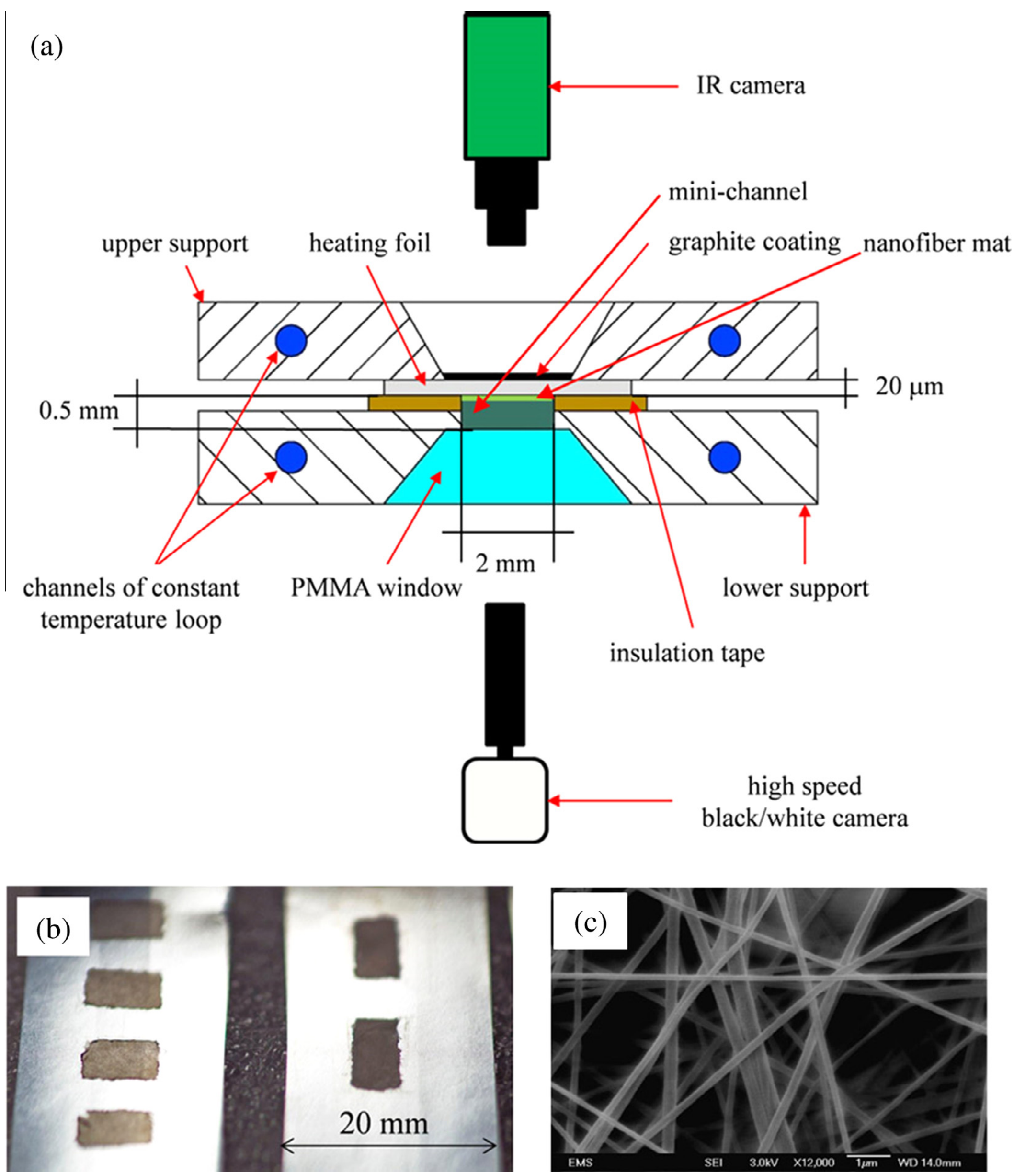

Fig. 1. (a) Schematic of experimental setup. (b) Periodic nano-textured sections on the mini-channel bottom. (c) A representative SEM image of nanofibers.